

# Finite Element Investigation of Nano-indentation of coated Stainless Steel

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**Abstract**—An finite element analysis was used to investigate the nano-indentation testing process in different kinds of coating on 316 Stainless Steel, in order to determine the properties of coating material and to investigate the influence of different of the material coating materials on 316 Stainless Steel. The finite element analysis was based elastic-plasticity properties of material. The results were three main points: 1) the simulation force-depth relationship was agreed with the experimental force-depth relationship for 316 stainless steel; 2) the range of Modulus of Elasticity for specific coating was determined as between 5GPa to 60GPa; 3) the influence of the thickness of coating material on the force indentation depth relationship was investigated. The project offers suggestions to further design of coating process research.

**Keywords:** coating material and property, nano-indentation, finite element analysis

## I. INTRODUCTION

The nano-indentation is an experiment for testing properties for coating and film and finite element method has been used in such research, for example [1]. Part of the objectives of the current project [2, 3] was specified as:

1) Testing for plate with only 316 Stainless Steel was simulated with FE, comparing with the result of experiment in nano-indentation in order to validate the correctness and accuracy of the FE analysis;

2) Determination the Modulus of Elasticity for specific ceramics coated 316 stainless steel, comparing with the result of experiment in nano-indentation;

3) Investigation the influence coating thickness on the force-indentation depth.

This paper reported the research work in order achieving the above objectives including the background information, the FE model developed and a series of case study.

## II. BACKGROUND INFORMATION

**Stainless Steel:** The property of stainless steel at room temperature is shown in Table 1 and Figure 1.

Table 1 Basic Property of Stainless Steel [4]

Modulus of Elasticity	Poisson Ratio	Yield Stress
193GPa	0.263	300MPa

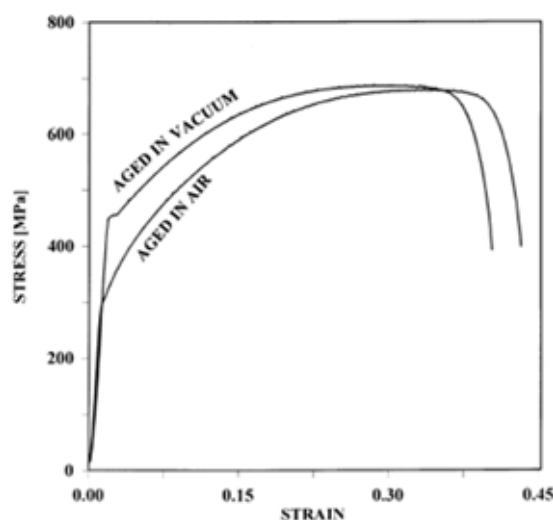


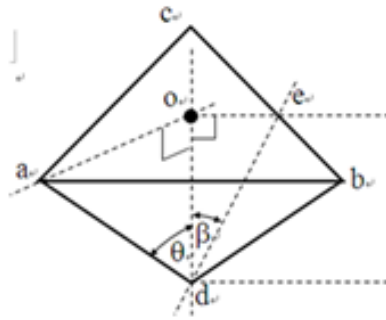
Figure 1: Relationship between stress and strain [5]

**Indenter:** The indenter was diamond. The geometry of the indenter was shown in Figure 1: Geometry of Indenter; the properties of the diamond was shown by Table 2: Synthetic diamonds values.

Table 2. Synthetic Diamonds Property

Young's Modules	Poisson's Ratio
1220 GPa	0.2

It is understood that the ceramic material is of brittle fracture nature and it is idealized as rigid plasticity for simplification and due to the limit of the I-DEAS software [6]. The base material stainless steel is modeled as elastic-plasticity accurately. It is also assumed no friction between the coating and indenter tip.



3-side pyramidal indenter tip  
 $\Delta abc$  is an equilateral base  
 $\beta = 53.4^\circ \pm 0.5^\circ$   
 $\theta = 69.6^\circ \pm 0.5^\circ$   
 $\sim 0.1-1 \mu\text{m}$  tip radius

Figure 2. The shape and dimension of 3-side pyramidal indenter tip

The FE analyses were organized as:

#### 1) Validating FE Model

Experimental nano-indentation test data of 316 stainless steel obtained from an industrial funded research project at Teesside University was used for validating the FE model developed.

#### 2) Determination of the value of Modulus of Elasticity for the coating material

A series of trial and error FE analysis were conducted with varying Young's modules of coating material. The FE obtained displacement and force relationship were used to determine the range of the Modulus of Elasticity through comparison with experimental data.

#### 3) Influence of coating thickness

A series of FE analysis with varying thickness of coating was conducted in order to obtain the quantitative results of its influence on the force-indentation depth.

### III. RESULTS

#### 3.1 Validating FE Model

The main aim was to validate the method of finite element techniques for the investigation of the nano-indentation test through the comparison of the predicted and the experimental force-depth relationship of 316 Stainless Steel. The FE model developed is illustrated in Figure 3.

The solution of model was illustrated as Fig. 3: the Model of Nano-indentation for 316 Stainless Steel. From this Figure, it was known that the maximum stress was at the top and it is contact stress, which was brought by the indenter.

Through the comparison of the FE prediction and experimental measurement shown in Figure 4, it is clearly that the FE prediction agrees very well with experimental data which confirms that the correctness and the accuracy of the FE model developed.

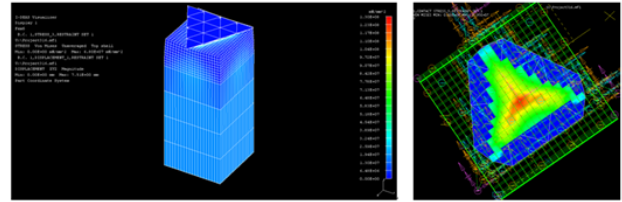


Figure 3 The FE Model and stress distribution

Table 3: The FE prediction of force and displacement during indenting pure stainless steel

Depth	Force
0nm	
150nm	
300nm	
450nm	
600nm	
750nm	

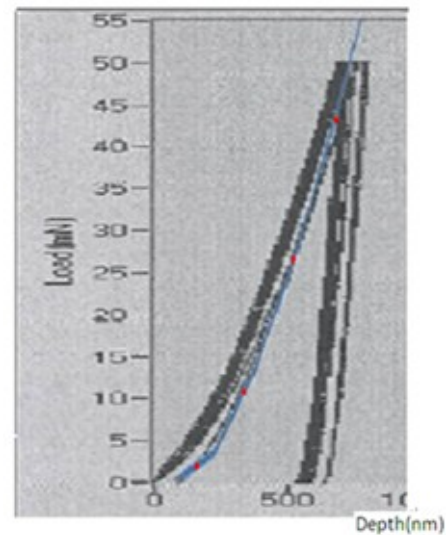


Figure 4 Comparison of FE predicted and experimental measured force-indentation depth relationship

#### 3.2 Determination of the Modulus of Elasticity for specific coated 316 stainless steel

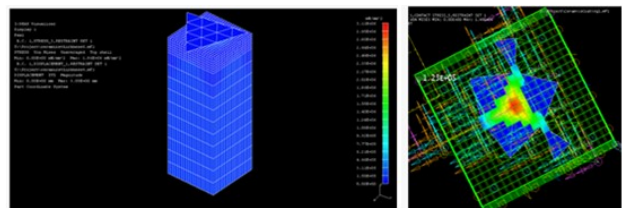


Figure 5 The FE Model and Contact of Top surface

Table 4 Trial values for the lower and upper limit of E

Lower Limit E	4.5GPa	5GPa	5.5GPa
Upper limit E	55GPa	60GPa	62GPa

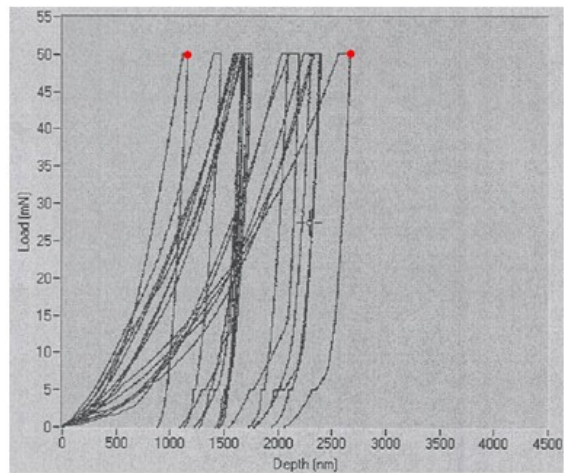


Figure 6 The load vs indentation depth with Modulus of Elasticity of 5 GPa and 60 GPa

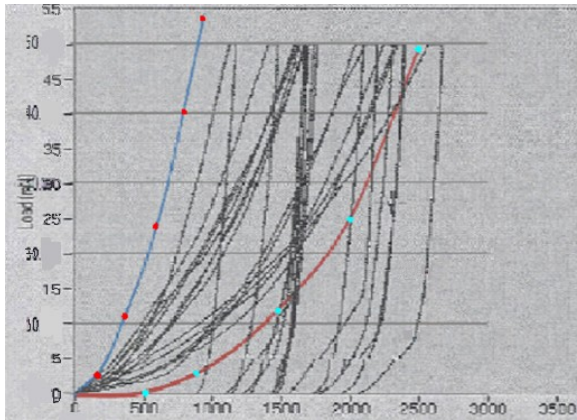


Figure 7 The force and indentation depth relationship

The FE model developed for this investigation and the top contact area are shown in Fig. 5. Fig. 6 shown the indentation depths for a given load assuming the coating material with E of 5 GPa and 60 GPa, which corresponded to the upper and lower limit of experimental observation. Fig. 7 shown the force indentation depth relationship during the whole indentation process, which clearly demonstrated a very good agreement between the FE prediction and experimental observation.

### 3.3 Influence of coating thickness

Three coating thickness were chosen, namely, 4  $\mu\text{m}$ , 5  $\mu\text{m}$ , and 6  $\mu\text{m}$  and the two values of E (5 GPa and 60 GPa) were used in the FE analysis. The typical FE Model is shown in Fig. 8 and the results are shown in Fig 9.

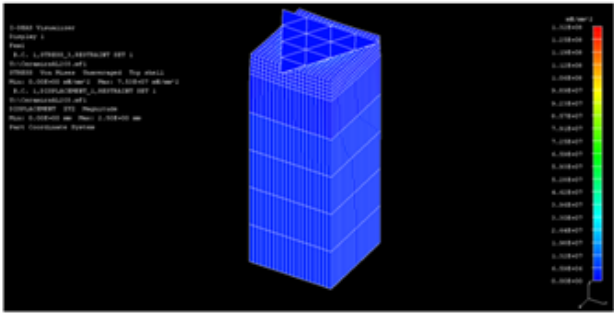


Figure 8 Typical FE Model

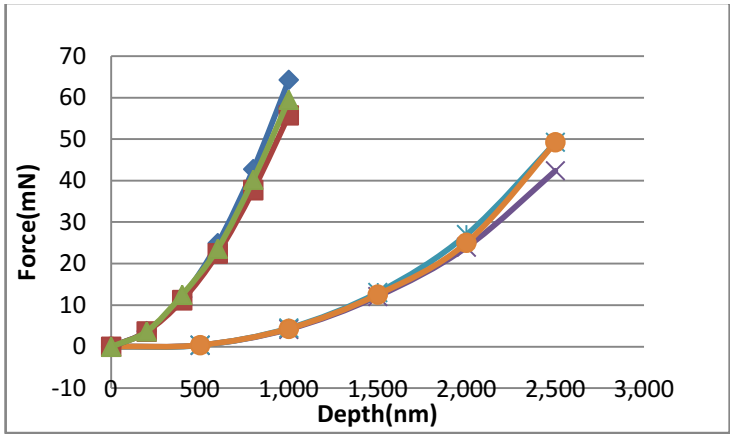


Figure 9 The effect of thickness on the force-displacement relationship:  $\diamond$  ,  $\circ$  , and  $\square$  for 4 , 5 , and 6 respectively

It is interesting to note from Fig. 9 that the thickness seems no significant influence on the force-indentation depth. This is supported by the fact observed from the Fig. 10, Fig. 11, Fig. 13 that the deformation under the tip of indenter is very localized within the coating, further increase of its thickness would not affect the relationship.

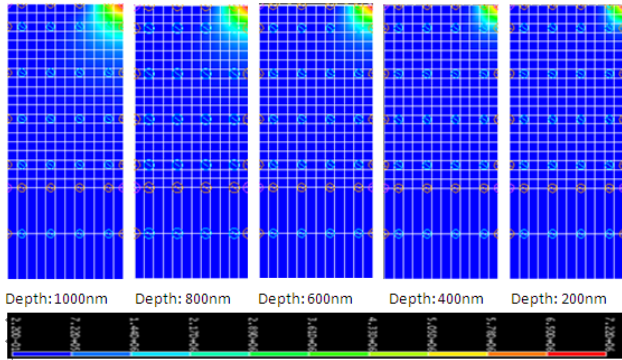


Figure 10a Effective Strain Distribution for Coating with 4 $\mu\text{m}$  Thickness and 5GPa Modulus of Elasticity



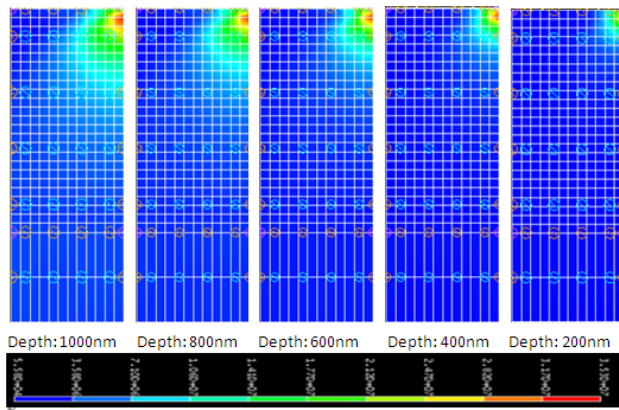


Figure 10b Effective Stress Distribution for Coating with 4μm Thickness and 5GPa Modulus of Elasticity

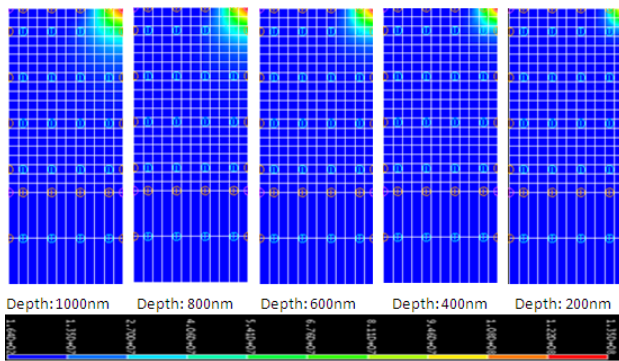


Figure 11a Effective Strain Distribution for Coating with 5μm Thickness and 5GPa Modulus of Elasticity

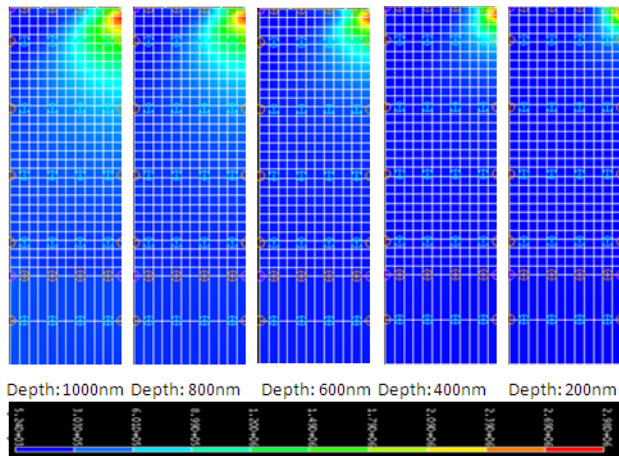


Figure 11b Effective Stress Distribution for Coating with 5μm Thickness and 5GPa Modulus of Elasticity

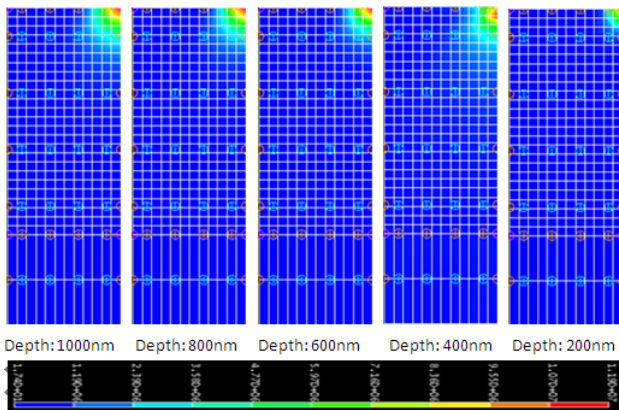


Figure 12a Effective Strain Distribution for Coating with 6μm Thickness and 5GPa Modulus of Elasticity

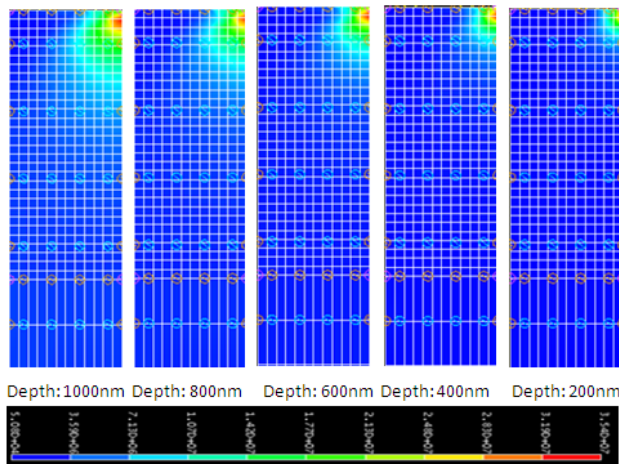


Figure 12b Effective Stress Distribution for Coating with 6μm Thickness and 5GPa Modulus of Elasticity

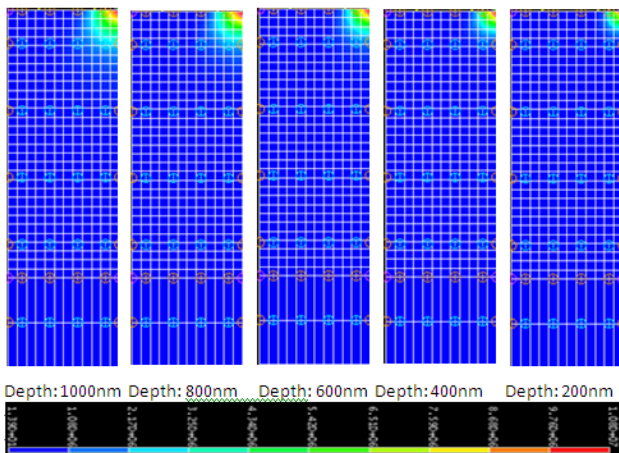


Figure 13a Effective Strain Distribution for Coating with 6μm Thickness and 5GPa Modulus of Elasticity

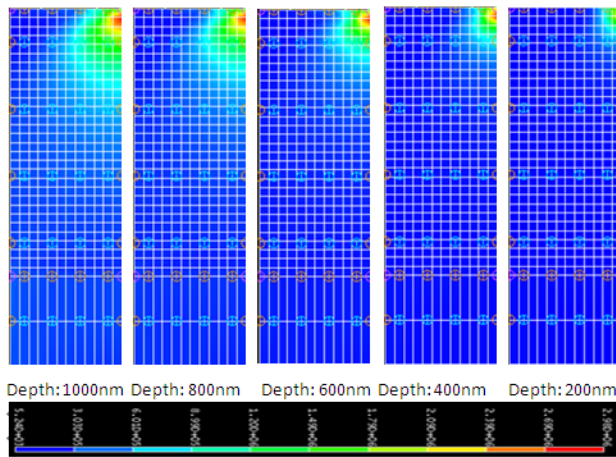


Figure 13b Effective Stress Distribution for Coating with  $6\mu\text{m}$  Thickness and 60GPa Modulus of Elasticity

#### IV. CONCLUSION

The overall conclusions are:

- 1) The FE analysis based on contact and elastic-plasticity model is reasonably accurate to depict the force-indentation depth;
- 2) The use of such FE model has been successfully used to determine the lower and upper limit of  $E$  for coating material;
- 3) It was revealed that when the coating thickness is in the order of 4 to 6  $\mu\text{m}$ , the thickness of coating has not significant influence on the force-indentation relationship. It is suggested that there is a lower bound for coating thickness which has practical significance in developing coated functional material.

#### V. REFERENCES

- [1] J. M. Lee, et al, "Identification of the bulk behaviour of coatings by nano-indentation test and FE-analysis and its application to forming analysis of the coated steel sheet," *Journal of Materials Processing Technology*, Vol. 187-188, pp.309-313, 2007
- [2] C. Jiang, Finite Element Investigation of Nano-indentation of coated stainless steel, final year project thesis, School of Science and Engineering, Teesside University, 2011
- [3] D. Liu, Finite Element Investigation of Nano-indentation of coated stainless steel, final year project thesis, School of Science and Engineering, Teesside University, 2011
- [4] A. Abduluyahed, and K. J. Kurzydłowski, "Tensile properties of a type 316 stainless steel strained in air and vacuum," *Materials Science and Engineering A*, vol.256, issue 1, pp.34-38, 1998
- [5] Micro Materials Ltd, [www.micromaterials.co.uk](http://www.micromaterials.co.uk)
- [6] I-DEAS